

# Non-thermal emission from supernova shock breakout and the origin of the X-ray transient associated with SN2008D

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**Abstract.** We suggest that non-thermal emission can be produced by multiple scatterings of the photons between the supernova ejecta and pre-shock material in supernova shock breakout. Such bulk-Comptonization process may significantly change the original thermal photon spectrum, forming a power-law non-thermal component at higher energies. We then show that the luminous X-ray outburst XRO081009 associated with SN2008D is likely to be such shock breakout emission from an ordinary type Ib/c supernova.

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## INTRODUCTION

Supernova shock breakout has been predicted for a few decades (e.g. [1]; [2]; [3]; [4]). In core collapse supernovae, a shock wave is generated which propagates through the progenitor star and ejects the envelope. As the shock propagates through the envelope, it is mediated by radiation: the post shock energy density is dominated by radiation, and the shock transition is mediated by Compton scattering. As the shock approaches the edge of the star, the optical depth of the plasma lying ahead of the shock decreases. At the radius where the optical depth drops to  $\sim c/v_s$ , where  $v_s$  is the shock velocity, the shock wave emerges through the surface and the radiation decouples, accompanied by a very bright ultraviolet/X-ray burst of radiation. The radiation spectrum is expected to be thermal-dominated. The term "shock breakout" is commonly used to refer to the emergence of the shock from the edge of the star. However, if the star is surrounded by an optically thick wind, the radiation mediated shock would continue to propagate into the wind, up to the point where the wind optical depth drops below  $\sim c/v_s$ . In this case, shock breakout, occurs as the shock propagates through the wind, at a radius which may be significantly larger than the star's radius. We use here the term "shock breakout" to denote this transition in general, regardless of whether it occurs as the shock reaches the edge of the star or further out within an optically thick wind.

This kind of radiation has previously never been directly detected from any normal supernovae due to its transient nature and its very early (minutes to hours) occurrence, in the absence of a suitably prompt trigger alert. On 2006 February 18, thanks to its sensitive gamma-ray trigger and rapid slewing capability, *Swift* has detected early thermal X-rays emission from a supernova (SN2006aj) associated with a low-luminosity GRB, namely GRB060218 (e.g. [5]), which has been interpreted as arising from the breakout of a radiation-dominated shock ([6]; [5]). The long duration ( $\sim 3000$  s) of the thermal X-ray emission of GRB060218/SN2006aj suggests that the shock breaks out from a dense, optically-thick wind surrounding the progenitor star<sup>1</sup>. The energetic of the thermal and non-thermal emission is of the order of  $10^{49}$  ergs, which is much larger than the predicted radiation energy from a normal type Ib/c supernova ([4]). Such a large energy release could be due to a larger kinetic energy in hypernova SN2006aj and/or an central engine that drives a jet which is, however, choked in the outward propagation.

On 2008 January 9, a bright X-ray outburst XRO080109 was serendipitously discovered during a scheduled *Swift* observations of the galaxy NGC 2770 ([8]). An ordinary type Ib/c supernova in coincident with this outburst was later spectroscopically identified and named SN2008D. This outburst has an energy of  $2 \times 10^{46}$  erg, which is three order

<sup>1</sup> Another possibility is that shock breaks out from an optically thick shell pre-ejected from the progenitor (the required shell mass is only  $10^{-7} M_\odot$ , see [5]).

of magnitudes smaller than even low-luminosity GRBs, but is astonishingly close to the predicted shock breakout radiation energy from a normal type Ib/c supernova ([4]).

The most mysterious thing of this X-ray outburst is the non-thermal spectrum, which is in contrast with the thermal spectrum predicted by the shock break theory. There is a general agreement that a power-law spectrum (with photon index  $\Gamma = 2.3 \pm 0.3$ ) provides a better fit for this x-ray outburst than a blackbody ([8]; [9]; [10]; [11]). The temporal evolution is characterized by a fast rise and exponential decay, with a FWHM duration about 100 s. The rise time is fitted to be  $63 \pm 7$  s ([8]).

## NON-THERMAL EMISSION FROM SUPERNOVA SHOCK BREAKOUT DUE TO BULK MOTION COMPTONIZATION

Blandford & Payne[12] first noted the importance of bulk motion acceleration of photons in a radiation-dominated shock. They found that photons are preferentially upscattered by the bulk motion rather than by the thermal motions of the electrons, and a power-law spectrum extending to high energies forms, when the electron thermal velocity is less than the shock velocity  $v_s$ . Repeated scatterings using the energy of the bulk motions of two approaching relativistic shells in the context of GRB internal shocks was studied by [13]. They found that the seed synchrotron photons can be boosted to much higher energies, which is confirmed by their Monte Carlo simulations. This process is equivalent to the Fermi acceleration mechanism of particles or photon scattering off Alfvén waves ([14]), but here the mechanism, instead, uses the relative bulk motion and accelerates photons.

Let's consider a mildly relativistic ejecta driving a radiation-dominated shock into the stellar envelope of supernova progenitor or into an optically thick wind (or pre-ejected shell) surrounding it. This mildly relativistic ejecta could result from the shock acceleration in the surface of the type Ib/c supernova progenitor ([4]) or from a jet that is choked and expands sideways in the outward propagation inside the star. Once the optical depth of the material in front of the shock drops below  $c/v_s$  (where  $v_s$  is the shock velocity), the photons escape and produce a breakout flash. Since the Thompson scattering optical depth is non-negligible in front of the shock while the shock is breaking out, some fraction of the thermal photons will be scattered back. The back-scattered photons will be scattered forward by the expanding ejecta or shocked plasma, boosting up their energy. The backward-forward scattering cycle may repeat itself many times for some fraction of the photons, boosting their energy by a large factor [7].

### A qualitative description

Ignoring the time dependence of  $\tau$ , the optical depth ahead of the shock, the physical situation is similar to that of Comptonization by a thermal electron plasma. In many cases, the electrons are cold and their momentum is dominated by the bulk motion. Assuming each scattering amplifies the photon energy by a factor  $A$ , the energy of a photon escaping after  $k$  scatterings is  $\epsilon_k = \epsilon_i A^k$ , where  $\epsilon_i$  and  $\epsilon_k$  are the initial and final photon energies respectively. For fixed  $\tau$ , a photon scattered by the ejecta has a probability  $1 - e^{-\tau}$  to be scattered back towards the ejecta, and a probability  $e^{-\tau}$  to escape. The probability for a photon to undergo  $k$  scatterings before escaping is  $(1 - e^{-\tau})^k$ , and since the photon energy is multiplied by  $A$  per scattering, the escaping photon intensity would have a power-law shape

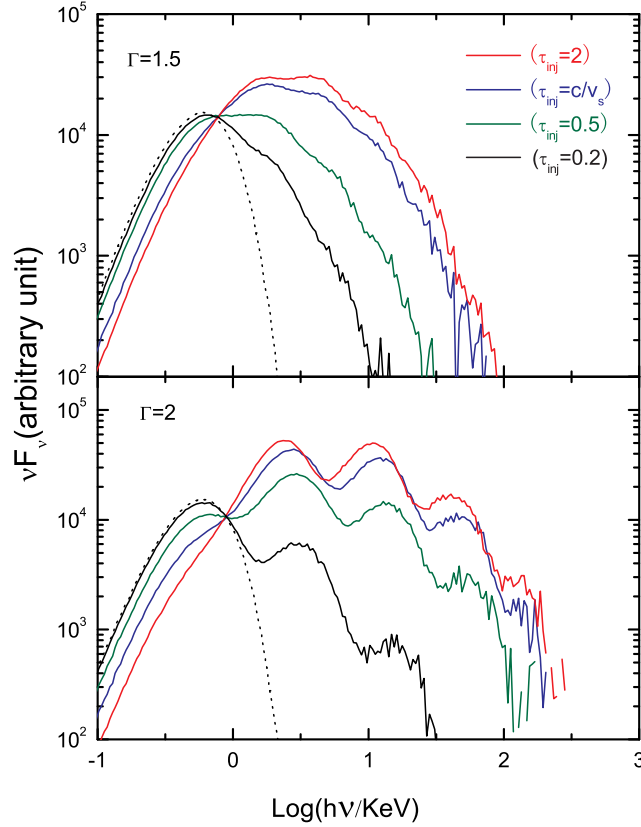
$$F(\epsilon_k) \sim F(\epsilon_i)(1 - e^{-\tau})^k \sim F(\epsilon_i)(\epsilon_k/\epsilon_i)^{-\alpha} \quad (1)$$

with

$$\alpha = -\ln(1 - e^{-\tau})/\ln A. \quad (2)$$

The photon energy amplification factor  $A$  is determined by the kinetic energy of the electrons. For trans-relativistic electrons and isotropic photon distributions,  $A \sim \Gamma^2(1 + \beta^2/3)$ . The power-law spectrum extends to a cutoff energy, which is the smaller of the electron kinetic energy,  $\sim (\Gamma - 1)m_e c^2$ , and its rest mass  $m_e c^2$  (due to the Klein-Nishina effect).

An important difference between the usual thermal electron (or bulk) Comptonization case and the current case is that in the present case the scattering optical depth decreases with time as the mildly relativistic ejecta moves outward. Initially, when the optical depth  $\tau \geq 1$ , the slope of  $vF_\nu$  is positive and most radiation is emitted at high energies. As  $\tau$  decreases, the spectrum becomes softer and softer, and at late times the spectrum is composed of a thermal peak plus a weak high-energy power-law tail. In general, we expect a noticeable spectral softening of the nonthermal emission



**FIGURE 1.** The time-integrated energy distribution of the escaping photons.  $10^6$  photons, with a black body distribution at  $k_B T_{th} = 0.15 \text{ KeV}$  (black dotted line), are injected at four different times, corresponding to optical depths of the pre-shocked medium of  $\tau_{inj} = 2, c/v_s, 0.5$  and  $0.2$ . The ejecta Lorentz factors are  $\Gamma = 1.5$  and  $\Gamma = 2$  for upper panel and lower panel respectively. Note, that the “humps” seen in the spectra are an artifact of the one-dimensional simulation, and are expected to be smoothed out in reality. See [7] for more details.

with time. This spectral softening is expected to be accompanied by a decrease in the Compton luminosity. At early time, when the effective Compton parameter  $Y = A(1 - e^{-\tau}) > 1$ , the Compton luminosity may exceed the thermal luminosity (it is limited by the kinetic energy of the ejecta  $E_k$ ). We expect the Compton luminosity to decrease with time, as  $Y$  decreases.

The x-ray or gamma-ray light curves produced in this model generally have a simple profile without multi-peak structure. The characteristic variability timescale  $\delta t$  of the burst is determined by the radius  $R$  where the optical depth of the material ahead of the shock drops to  $\sim 1$ , i.e.  $\delta t \sim R(\tau = 1)/c$  (If the stellar wind surrounding the progenitor were optically thin everywhere, the shock would break out from the SN progenitor stellar envelope and the variability time would be about  $R_*/c$ , where  $R_*$  is the stellar radius.)

### Monte Carlo simulation of photon “acceleration”

In order to understand the photon “acceleration” mechanism in the time-dependent case, we carried out a Monte Carlo simulation of repeated Compton scattering during shock breakout from a dense stellar wind [7]. We approximate the hydrodynamics of the problem as follows. We consider the mildly relativistic ejected shell to act as a piston with

a time-independent bulk Lorentz factor  $\Gamma$  and an infinite optical depth  $\tau_{ej}$ . Since the stellar wind swept up by the ejecta is not sufficient to decelerate it, the constant velocity of the interface is justified. This “piston” drives a shock into the surrounding medium, where the density profile is assumed to follow  $n \propto R^{-2}$ . We assume the shock width to be infinitesimal. There are three distinct regions in this picture: The moving piston, the shocked medium and the pre-shocked medium. The shocked medium is considered to form a homogeneous shell, and the electrons are regarded as cold, with a bulk velocity same as that of the ejecta. The velocity of the shock front can then be obtained consistently from the shock jump condition. We further simplify the problem by considering a one-dimensional situation, where the motion of the photons is confined to one dimension, forward or backward relative to the shock expansion direction. The photons are injected at the shock front and would then be repeatedly scattered among these three components until they escape out to a sufficiently further region. Our simulation takes into account the proper possibility of photon scattering by each of the three components (with the appropriate photon energy gain or loss). The photon scattering probability by the unshocked wind and shocked wind is determined by the optical depth of each component, while the piston is regarded as a mirror since it has a larger optical depth much larger than unity.

We study the spectra of escaping photons, which result from the “injection” of photons at the shock front at various radii, corresponding to various values of  $\tau$  at the injection time, denoted by  $\tau_{inj}$ . The photons are treated as “test particles”, and their scattering history is followed as the shock expands and  $\tau$  decreases. The resulting time-integrated  $\nu F_\nu$  spectra are given in Fig. 1 for two values of  $\Gamma$ ,  $\Gamma = 2$  and  $\Gamma = 1.5$ . The red, blue, olive and black curves describe the spectrum of escaping photons resulting from the injection of a thermal distribution of photons at  $\tau_{inj} = 2, c/v_s, 0.5$  and  $0.2$  respectively. The injected photons are assumed to have a thermal spectrum with  $T = 0.15$  keV. The “humps” seen in the simulated spectra correspond to different orders of Compton scattering, with two nearby humps separated by  $\sim \Gamma^2$ . These humps appear because we do not consider in our one-dimensional simulation the angular distribution of scattered photons. In reality, these humps are expected to be smoothed out. Fig. 1 demonstrates that a significant fraction the thermal photons that are injected at optical depth  $\tau_{inj} \sim 1$ , where the photons are expected to escape the shock, may be “accelerated” to high energy. The resulting non-thermal component may carry a significant fraction of the shell energy, and its luminosity could exceed that of the thermal component, depending on the value of  $\Gamma$ . As expected, the spectrum depends on  $\Gamma$  and on  $\tau_{inj}$ , with harder spectra obtained for larger values of  $\Gamma$  and  $\tau_{inj}$ . Note that the spectra are steeper (softer) at high energies, due to the longer time required for acceleration to higher energies, which implies a significant decrease in  $\tau$  during the acceleration process.

## SHOCK BREAKOUT ORIGIN OF THE X-RAY OUTBURST XRO 080109

Although the thermal x-ray component is not identified in XRO 080109, there are a few facts that favor the shock breakout interpretation: 1) smooth light curve—consistent with shock breakout prediction; 2) low total radiation energy of  $10^{46}$  erg—close to the theory prediction for a normal type Ib/c SN; 3) early (few days) decline in the optical emission from SN, probably optical emission from the adiabatically cooling ejecta heated by shock breakout ([6]).

The non-thermal spectrum of XRO 080109 can be due to the bulk-comptonization of the thermal shock breakout photons. Then, the peak of the thermal component should be not larger than 0.3 keV (the low threshold energy of XRT) so that the thermal component was not detected by XRT. Since the Compton  $Y$  parameter is typically of the order of unity, the energy in non-thermal emission should be roughly comparable to that in thermal energy. From these simple arguments, we now derive the constraint on the shock parameters, following [6].

For a strong radiation-dominated shock, the radiation pressure  $p = f(\Gamma\beta)^2 \rho c^2$ , where  $\rho$  is the mass density of the pre-shocked density and  $f \simeq 0.8$  for trans-relativistic shock ([6]). The post shock temperature  $T_d$  is related to the postshock pressure by  $aT_d^4 = 3p$ , and the observed temperature is  $T = \gamma_d T_d$ , where  $\gamma_d$  is the Lorentz factor of the downstream flow. The temperature of the shock breakout thermal emission  $T$  is related to the velocity of the shock and photosphere radius by

$$aT^4 = 3f(\Gamma\beta)^2 \rho c^2 \gamma_d^4 \simeq (\Gamma\beta)^6 \rho c^2 = (\Gamma\beta)^6 c^2 \left( \frac{1}{\kappa R_{ph}} \right), \quad (3)$$

where the optical depth  $\tau(R) = \kappa R \rho$  with  $\tau(R_{br}) = \tau(R_{ph}) = 1$  at the breakout radius  $R_{br}$  for trans-relativistic shock and  $\kappa$  is the Thomson opacity.

Assuming the energy in the thermal component is comparable to that in the non-thermal one (which is likely for a trans-relativistic shock), i.e.  $E_{th} \sim 2 \times 10^{46} \text{erg}$ , we can obtain, from Eq.(2) in ref.[6],

$$(\Gamma\beta)^2 \simeq \frac{E_{th}}{0.5 \times 4\pi R_{ph}^3 \rho c^2} = \frac{E_{th} \kappa}{2\pi R_{ph}^2 c^2}. \quad (4)$$

Combining Eqs.(3) and (4), we obtain

$$\Gamma\beta = 1.1 \left( \frac{T}{0.1 \text{KeV}} \right)^{2/7} \left( \frac{E_{th}}{2 \times 10^{46} \text{erg}} \right)^{1/28} \left( \frac{\kappa}{0.2 g^{-1} \text{cm}^2} \right)^{3/28} \quad (5)$$

and

$$R_{br} = 7 \times 10^{11} \left( \frac{T}{0.1 \text{KeV}} \right)^{-4/7} \left( \frac{E_{th}}{2 \times 10^{46} \text{erg}} \right)^{3/7} \left( \frac{\kappa}{0.2 g^{-1} \text{cm}^2} \right)^{2/7} \text{cm}, \quad (6)$$

where  $\kappa \simeq 0.2 g^{-1} \text{cm}^2$  is the Thompson opacity for ionized He wind.

Requiring  $T \leq 0.1 \text{KeV}$  to account for the non-detection of the thermal peak, we derive the constraints on the shock velocity  $\Gamma\beta$  and breakout radius  $R_{br}$ , i.e.

$$\Gamma\beta \leq 1.1 \left( \frac{E_{th}}{2 \times 10^{46} \text{erg}} \right)^{1/28} \left( \frac{\kappa}{0.2 g^{-1} \text{cm}^2} \right)^{3/28}, \quad (7)$$

$$R_{br} \geq 7 \times 10^{11} \left( \frac{E_{th}}{2 \times 10^{46} \text{erg}} \right)^{3/7} \left( \frac{\kappa}{0.2 g^{-1} \text{cm}^2} \right)^{2/7} \text{cm}. \quad (8)$$

We note that there is a misuse of the relation  $L_{rad} = 4\pi R^2 \sigma T^4$  to derive the shock breakout radius in some papers, where  $T$  is the radiation temperature. This is because the light travel time ( $R/c$ ) will lengthen the breakout emission duration significantly and render the observed radiation luminosity lower than  $4\pi R^2 \sigma T^4$  significantly (see also [4]). So one would get a much smaller radius for shock breakout if this incorrect relation is used.

The rise time of the x-ray transient is about 60 s ([8], implying a radius for the emitting region

$$R_{ph} \simeq c\delta t = 2 \times 10^{12} \text{cm}, \quad (9)$$

which is consistent with the above inferred breakout radius. Since this radius is larger than that of the WR progenitor, the shock must break out from the surrounding stellar wind. From  $\tau = 1$  at  $R_{br}$ , we derive  $\dot{M} = 4\pi v_w R_{br} / \kappa \geq 7 \times 10^{-5} M_\odot \text{yr}^{-1} (\kappa / 0.2 g^{-1} \text{cm}^2)^{-1}$  for  $v_w = 1000 \text{Kms}^{-1}$ .

So we need a trans-relativistic shock with  $\Gamma\beta \leq 1$  at the time when shock is breaking out. This can be achieved for a normal type Ib/s SN explosion, according to the calculation of [4]. Substituting the inferred ejecta kinetic energy ( $E_K = 2 - 4 \times 10^{51} \text{erg}$ ) and mass ( $M_{ej} = 3 - 5 M_\odot$ ) of SN 2008D and a typical Wolf-Rayet star radius of  $R = 10^{11} \text{cm}$  into Eq.(32) of [4], the maximum velocity that the radiation-dominated shock can reach is trans-relativistic.

With a velocity  $0.5 \leq \Gamma\beta \leq 1$ , the energy amplification factor for one Compton scattering is

$$A = \Gamma^2 (1 + \beta^2/3) = 1.5 - 2.3 \quad (10)$$

which implies an equivalent Compton parameter  $Y = A(1 - e^{-\tau}) \simeq 1$ , consistent with our earlier assumption.

## DISCUSSIONS

Chevalier & Fransson [15] questioned the bulk Comptonization mechanism for XRO080109/SN2008D by arguing that "the breakout radiation is capable of accelerating the matter ahead of the shock front so that the formation of the gas dominated shock is delayed". This is not true because as long as there is a converging flow (in our case the supernova ejecta moving relative to the pre-shock matter), the repeated scatterings will occur and the bulk Comptonization will work. So the formation of an viscous shock is not a necessity for the bulk Comptonization process. Also, for a type Ib/c supernova shock that reach a mildly-relativistic velocity, the radiation is actually incapable of accelerating the matter ahead of the shock front to such a mildly-relativistic velocity, according to our calculation given below. The radiative acceleration is

$$g_R = \frac{\kappa L_{rad}}{4\pi R^2 c} = 5 \times 10^7 \left( \frac{\kappa}{0.2 g^{-1} \text{cm}^2} \right) \left( \frac{L_{rad}}{10^{42} \text{ergs}^{-1}} \right) R_{12}^{-2} \text{cm s}^{-2}. \quad (11)$$

So the maximum velocity that the matter ahead of the shock front be accelerated to is

$$v_m = g_R \Delta t = 5 \times 10^9 \left( \frac{\kappa}{0.2 g^{-1} cm^2} \right) \left( \frac{L_{rad}}{10^{42} \text{ergs}^{-1}} \right) R_{12}^{-2} \left( \frac{\Delta t}{100 \text{s}} \right) \text{cms}^{-1}, \quad (12)$$

which is below the mildly-relativistic velocity of the shock front.

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